AWAKE Status Report

Allen Caldwell
Max-Planck-Institut für Physik
October 16, 2019

1. Introduction
2. Summary of Run 1 results to date
3. Ongoing data analysis
4. Run 2 plans

AWAKE

- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Use SPS proton beam as drive beam (Single bunch 3e11 protons at 400 GeV)
  - Inject electron beam as witness beam

- Proof-of-Principle Accelerator R&D experiment at CERN
  - First proton driven plasma wakefield experiment worldwide

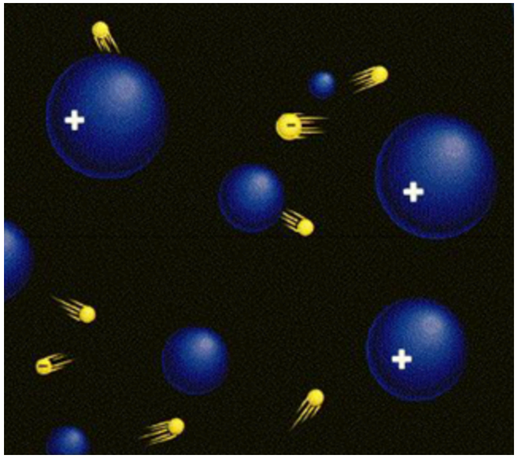
AWAKE

AWAKE Collaboration: 22 Institutes world-wide:

- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, London, UK
- UNIST, Ulsan, Republic of Korea
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE - Instituto Universitéario de Lisboa, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk, Russia
- GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL, Lausanne, Switzerland

+ 2 associate members:

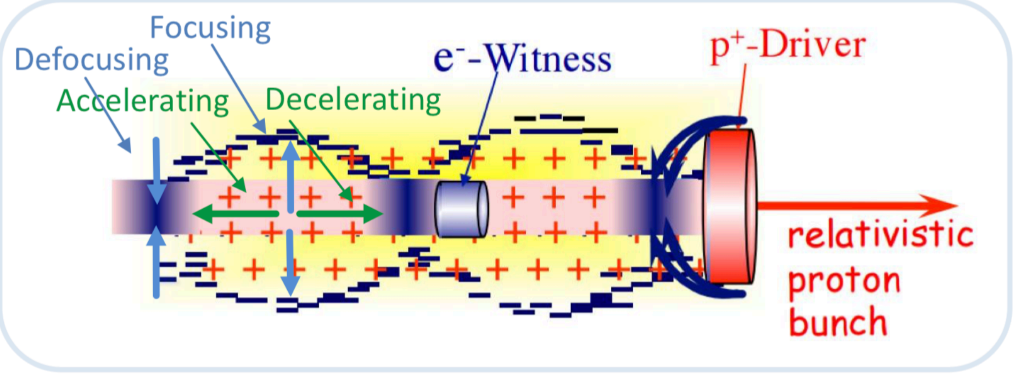
Jena University
University of Texas



A plasma: collection of free positive and negative charges (ions and electrons). Material is already broken down. A plasma can therefore **sustain very high fields.**

E. Adli, Oslo

P. Muggli, MPP



An intense **particle beam**, or intense **laser beam**, can be used to drive the plasma electrons.

Plasma frequency depends only on density:

relativistic drive beam

$$\omega_p^2 = \frac{4\pi n_p e^2}{m} \qquad \lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1\cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$$

Ideas of **~100 GV/m** electric fields in plasma, using 10^{18} W/cm^2 lasers: 1979 **T.Tajima and J.M.Dawson** (UCLA), Laser Electron Accelerator, Phys. Rev. Lett. 43, 267–270 (1979).
Using partice beams as drivers: P. **Chen et al**. Phys. Rev. Lett. 54, 693–696 (1985)

Why protons?

Energy Budget:

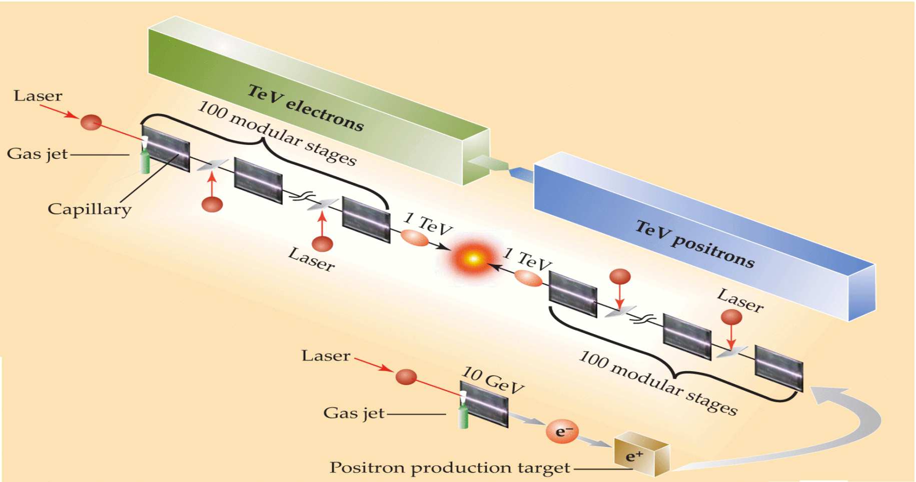
Witness:
10^{10} particles @ 1 TeV ≈ few kJ

Drivers:
PW lasers today, ~40 J/Pulse

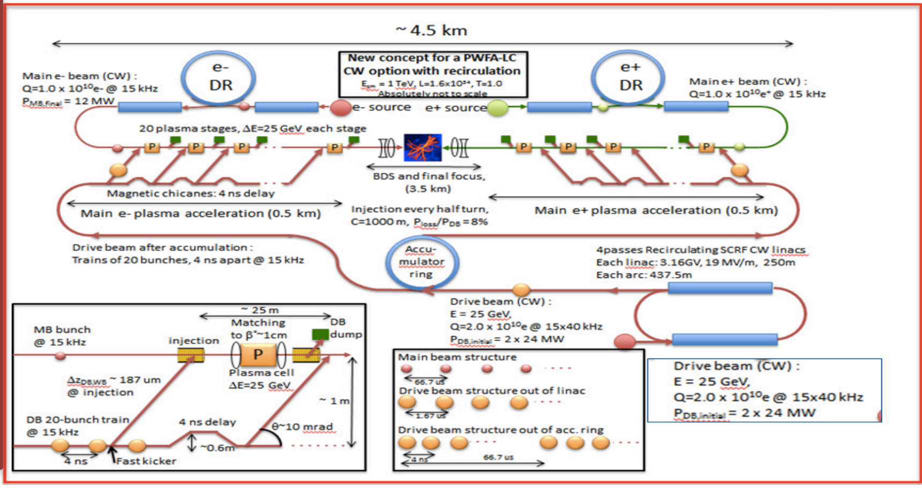
FACET (e beam, SLAC), 30J/bunch

SPS@CERN 20kJ/bunch
LHC@CERN 300 kJ/bunch

Staging Concepts



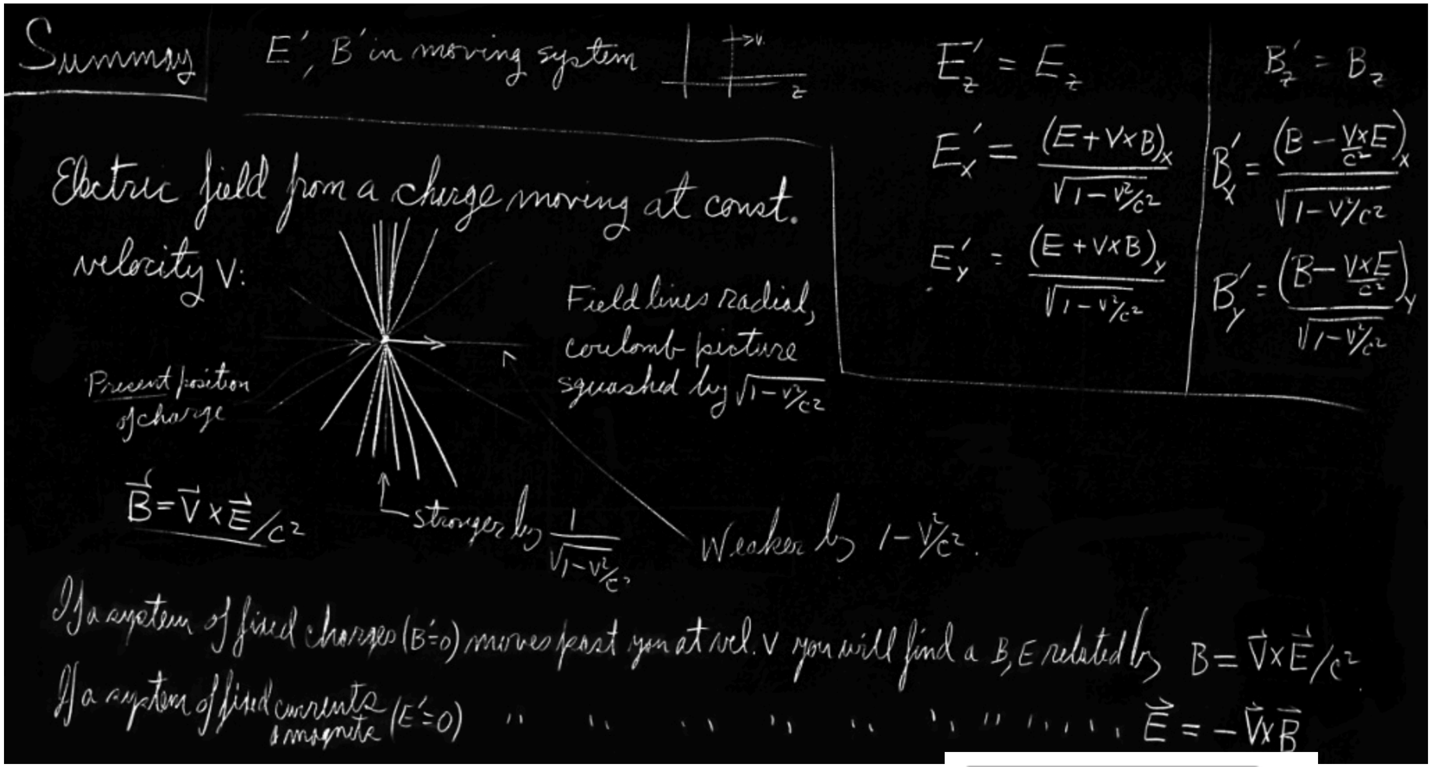
Leemans & Esarey, Phys. Today ***62 #3*** *(2009)*



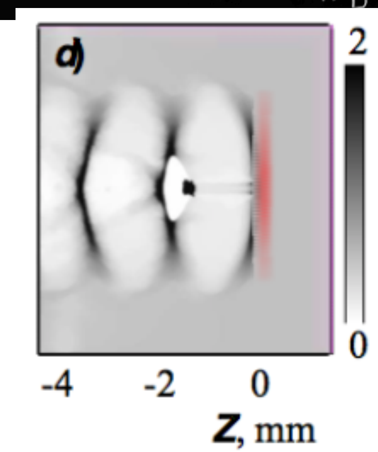
E. Adli et al. arXiv:1308.1145,2013

Small beam dimensions required !

Feynman Lectures, CalTech



$$E_{z,\max} \approx 2\ \mathrm{GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100\ \mu\mathrm{m}}{\sigma_z}\right)^2$$



$$\sigma_z = 100\ \mu\mathrm{m}$$

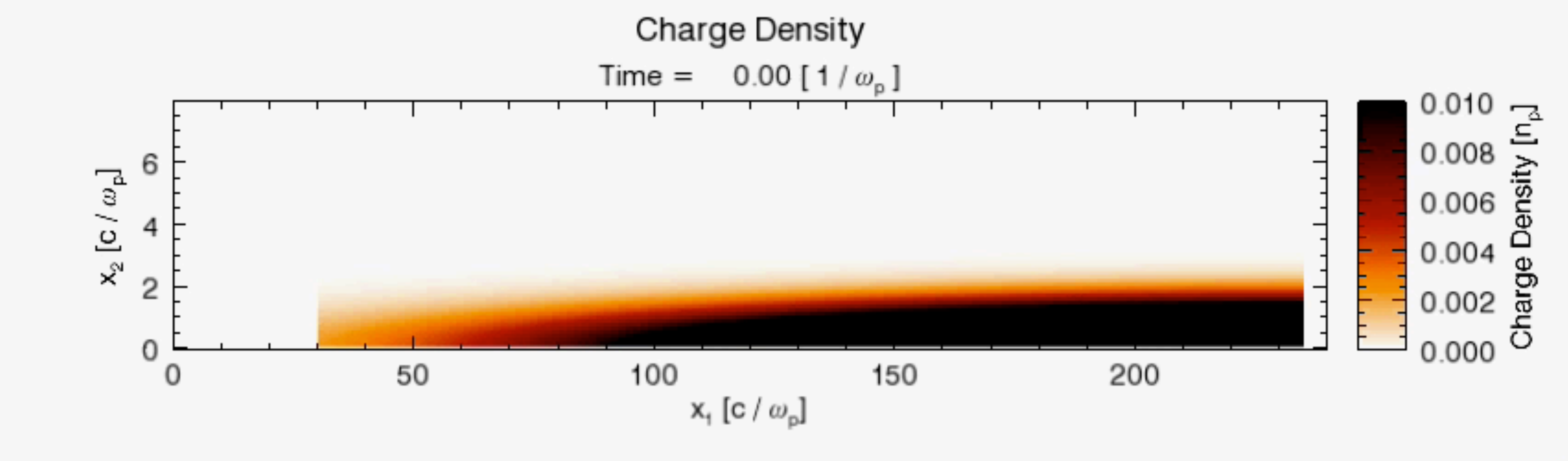
Caldwell, Lotov, Pukhov, Simon Nat. Phys. (2009)

Today's proton beams have $\sigma_z \approx 10\ \mathrm{cm}$

Modulated Proton Beam

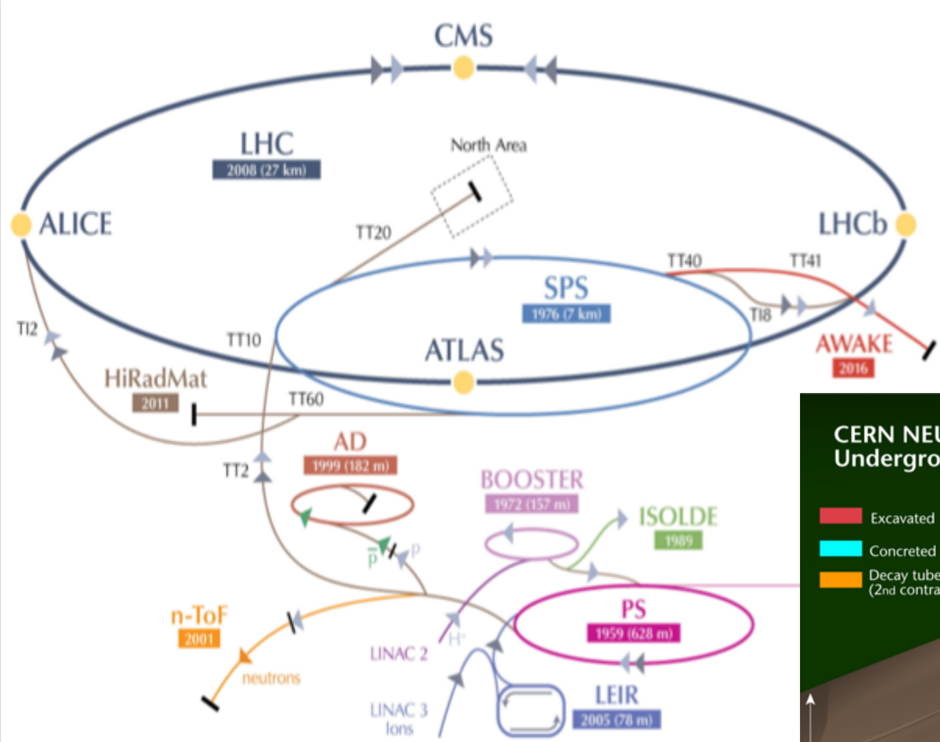
Solution ! microbunches are generated by the interaction between the bunch and the plasma. The microbunches are naturally spaced at the plasma wavelength, and act constructively to generate a strong plasma wake. Investigated both numerically and analytically.

N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)



Propagation of a 'cut' proton bunch in a plasma. From Wei Lu, Tsinghua University

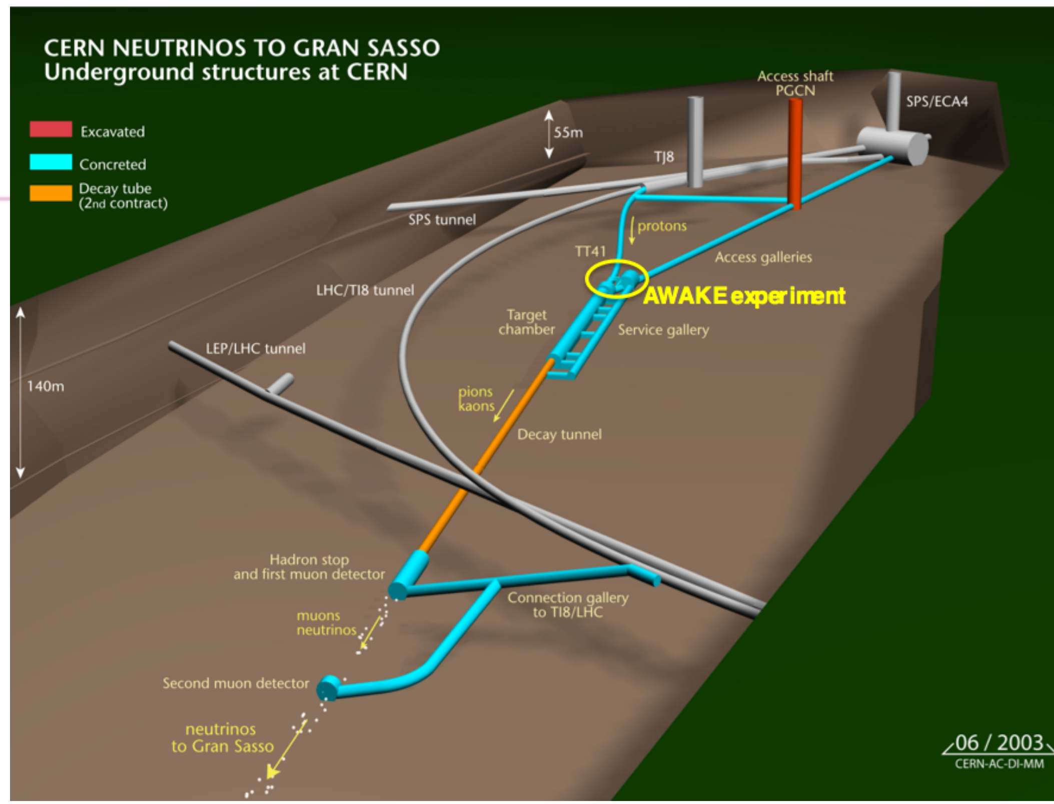
AWAKE at CERN



AWAKE is installed in

CNGS Facility (CERN Neutrinos to Gran Sasso)

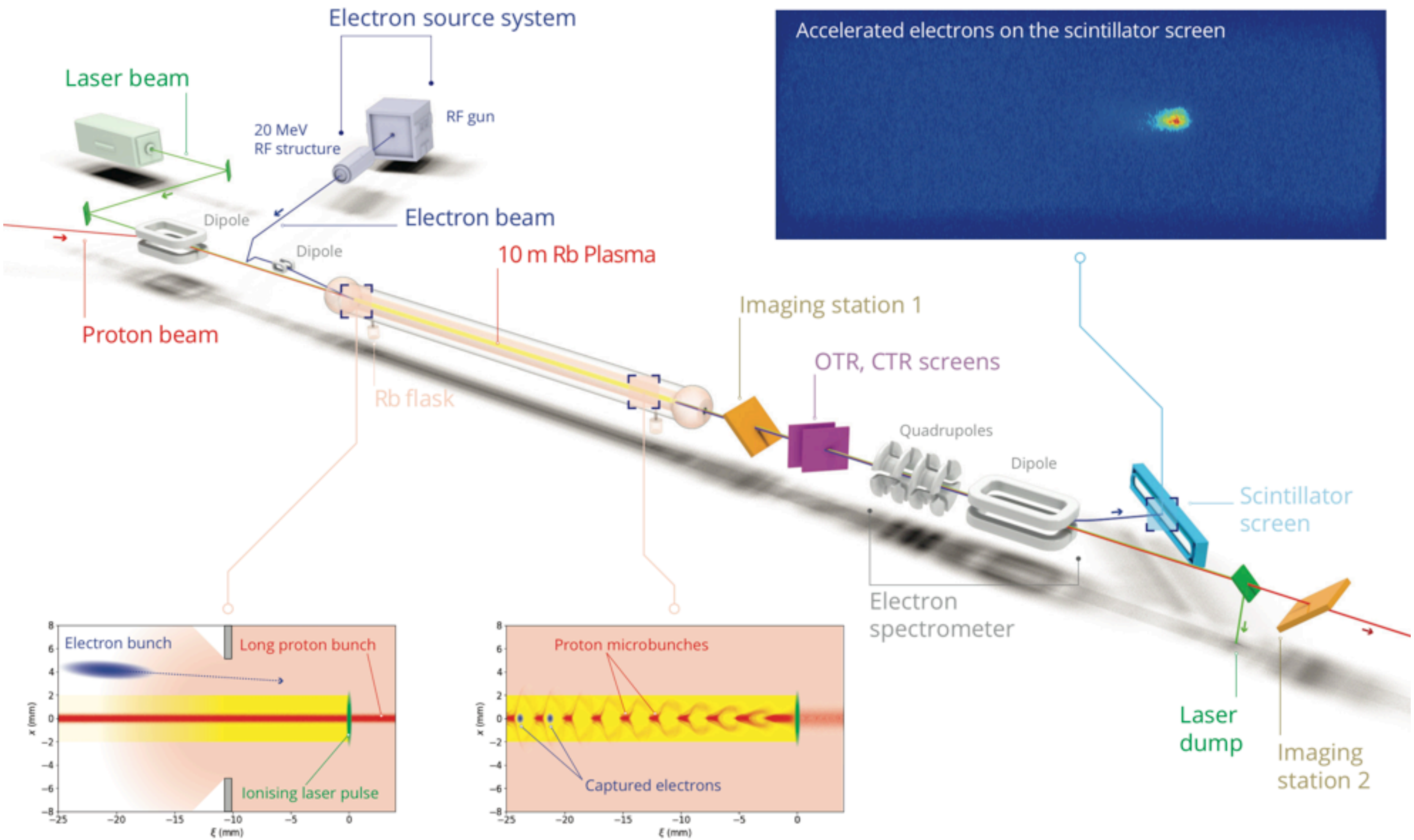
→ CNGS physics program finished in 2012



A. Caldwell et al., "Path to AWAKE: Evolution of the concept", Nucl. Instrum. Meth. A829 (2016) 3-16; E. Gschwendtner et al. [AWAKE Collaboration], "AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN," Nucl. Instrum. Meth. A829, 76 (2016).

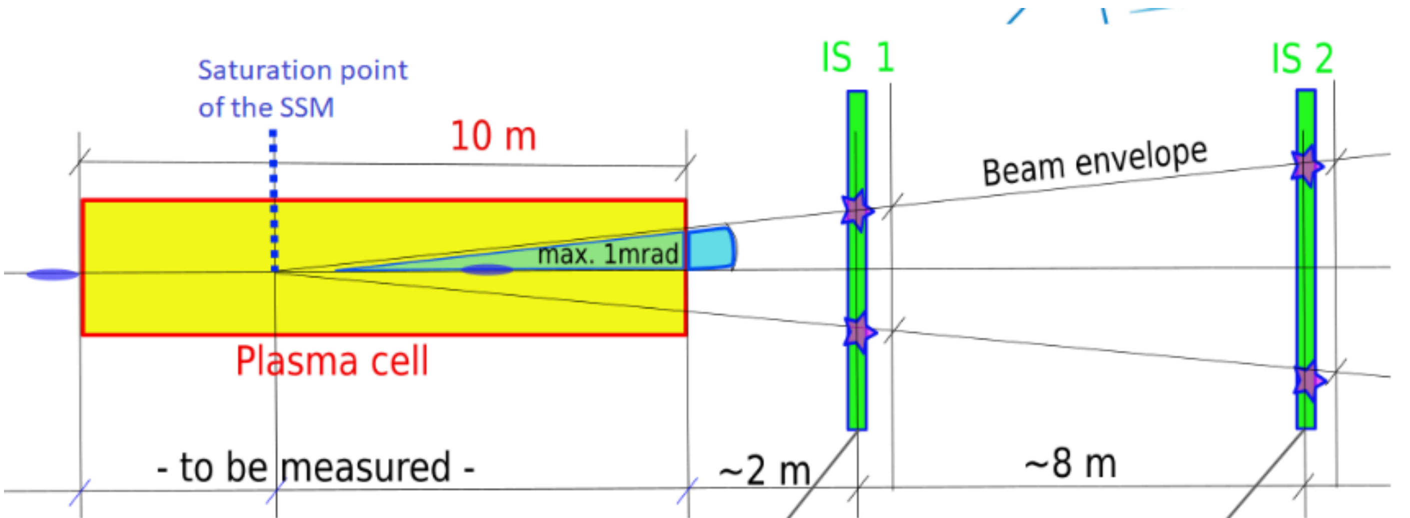
Run I (2016-2018) - summary

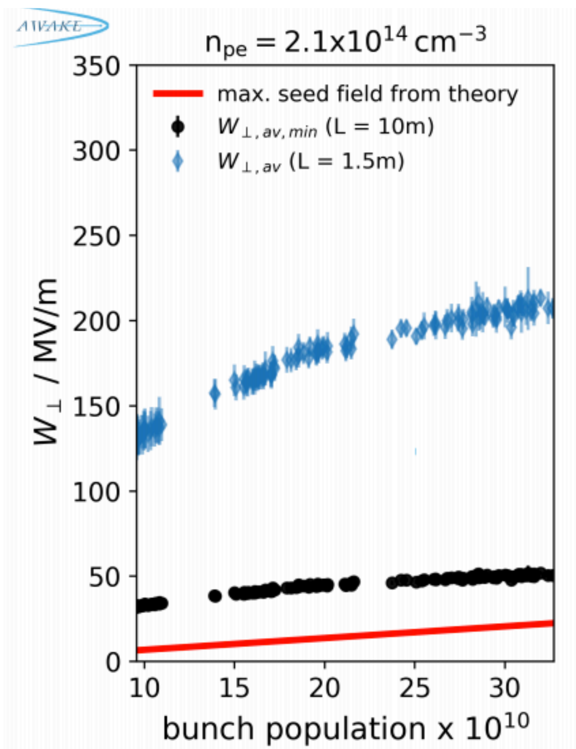
- **Phase 1: Understand the physics of self-modulation.**
- **Phase 2: Probe the accelerating wakefields with externally injected electrons.**



AWAKE

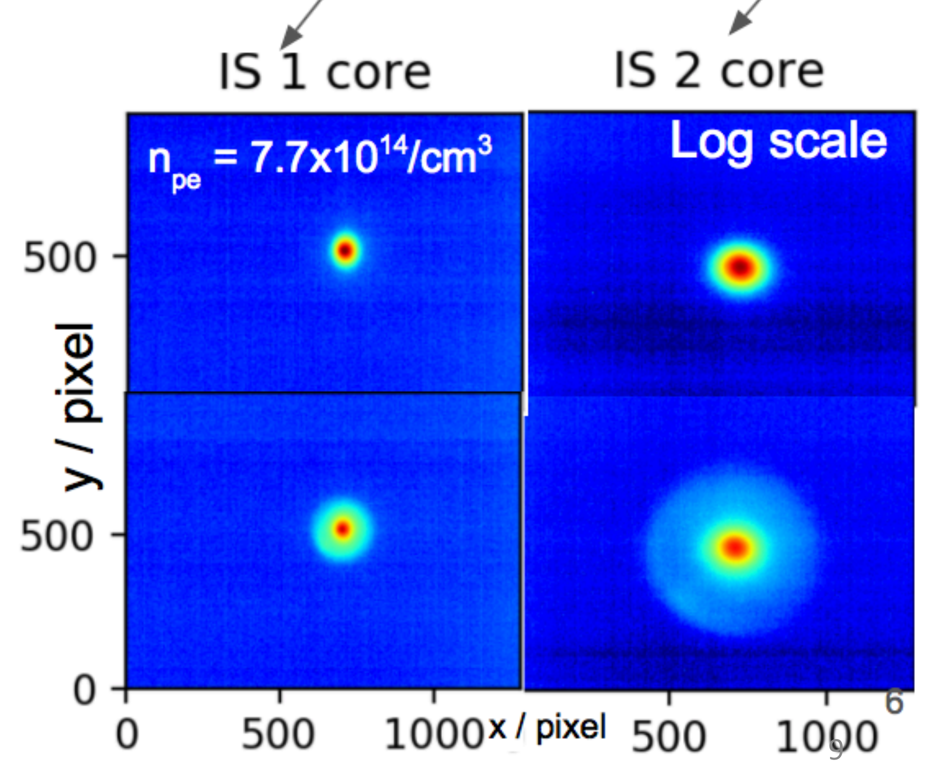
Transverse Modulation - expanding proton bunches



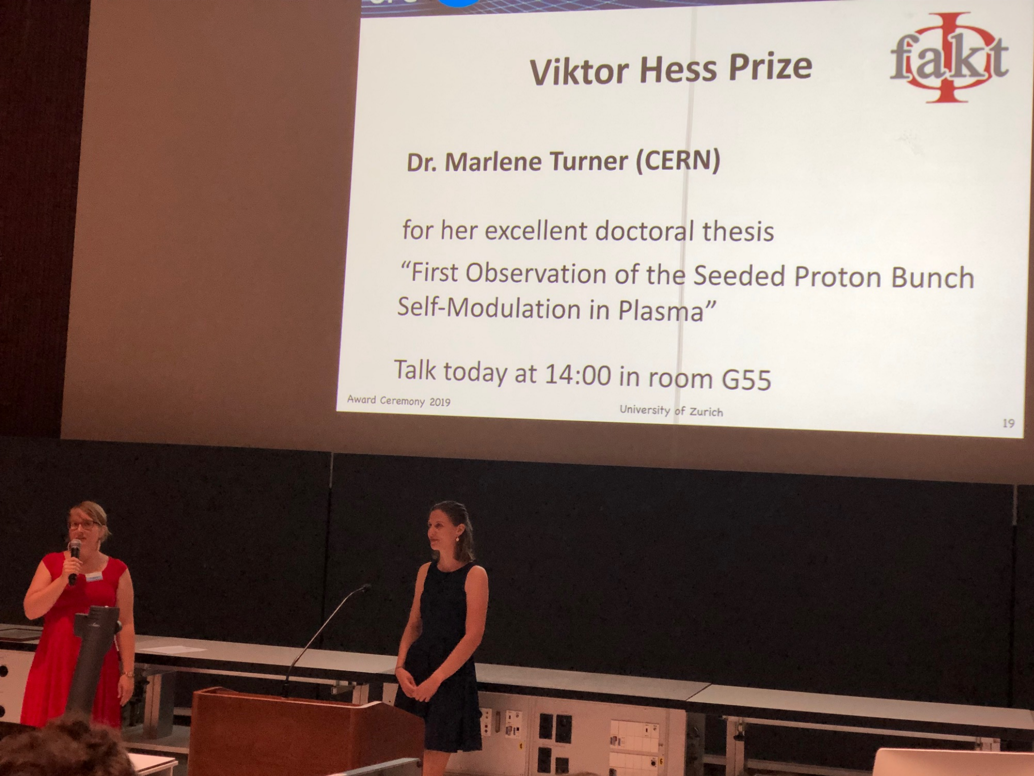


Plasma off:

Plasma on:



M. Turner et al., (AWAKE Collaboration) PRL **122**, 054801 (2019)



Dr. Marlene Turner

Victor-Hess-Prize awarded by the The Nuclear and Particle Physics Section of the Austrian Physicist Society,

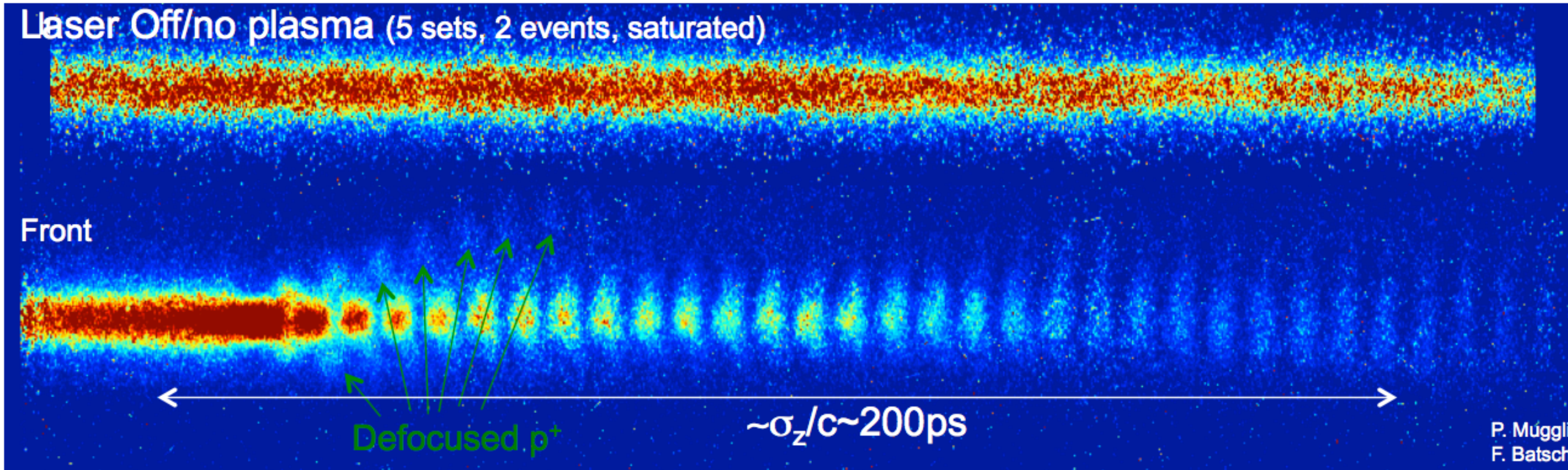
prize given at the Joint Annual Meeting of the Swiss/Austrian Physicist Society , 26-30 August 2019, Zurich, Switzerland.

John Dawson Thesis Prize, in the area of plasma accelerators driven by laser and/or particle beams.

Awarded at the LPAW, Laser and Plasma Accelerators Workshop 2019, Split, Croatia, 5-10 May 2019.

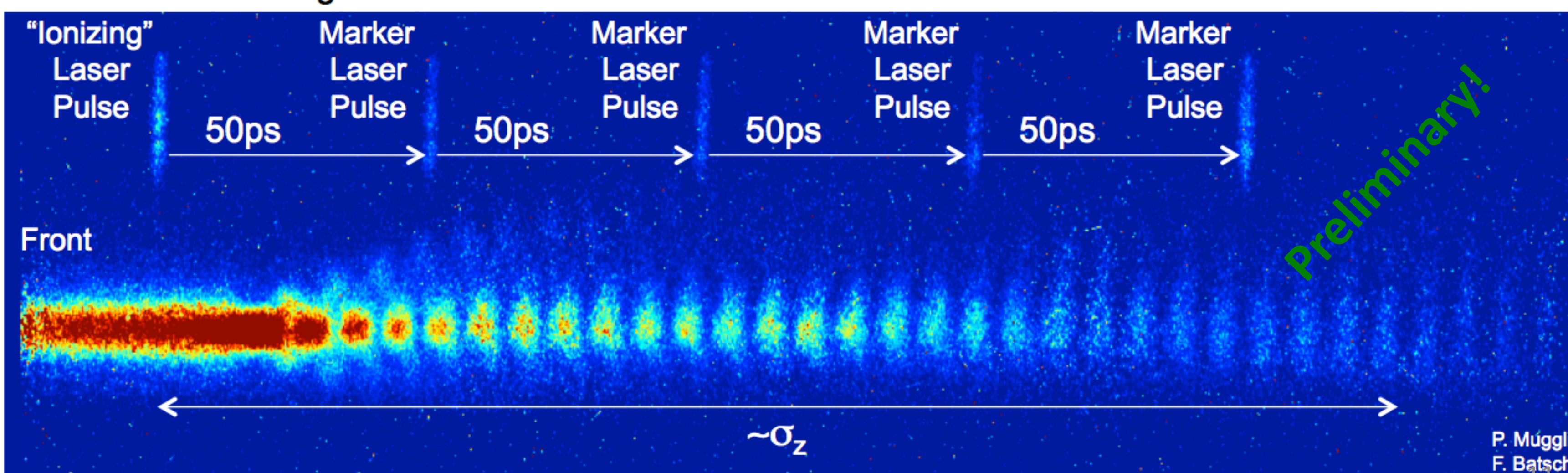
Seeded self-modulation works

Streak camera Images



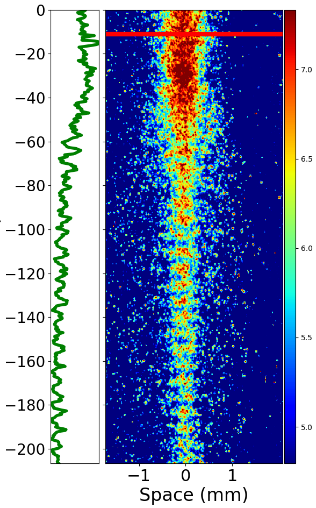
Streak camera Images

10 events each

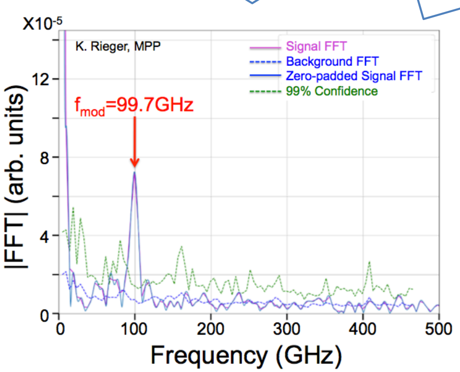


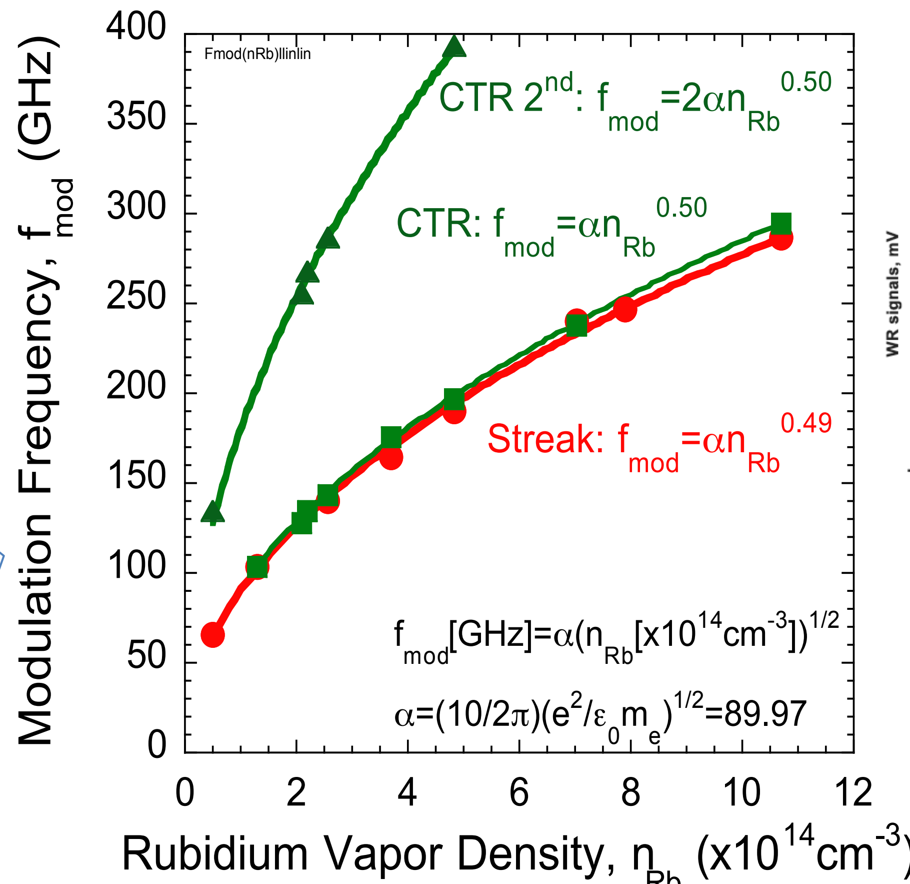
AWAKE

Modulation at the expected frequency

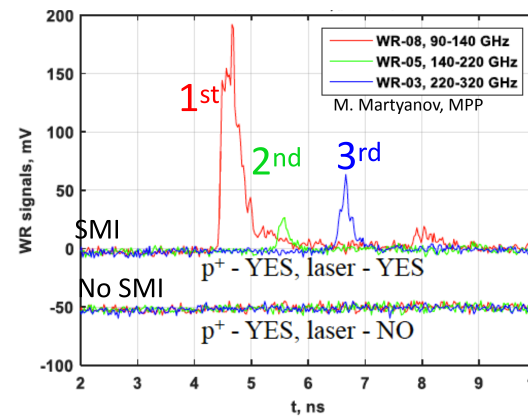


FFT





CTR



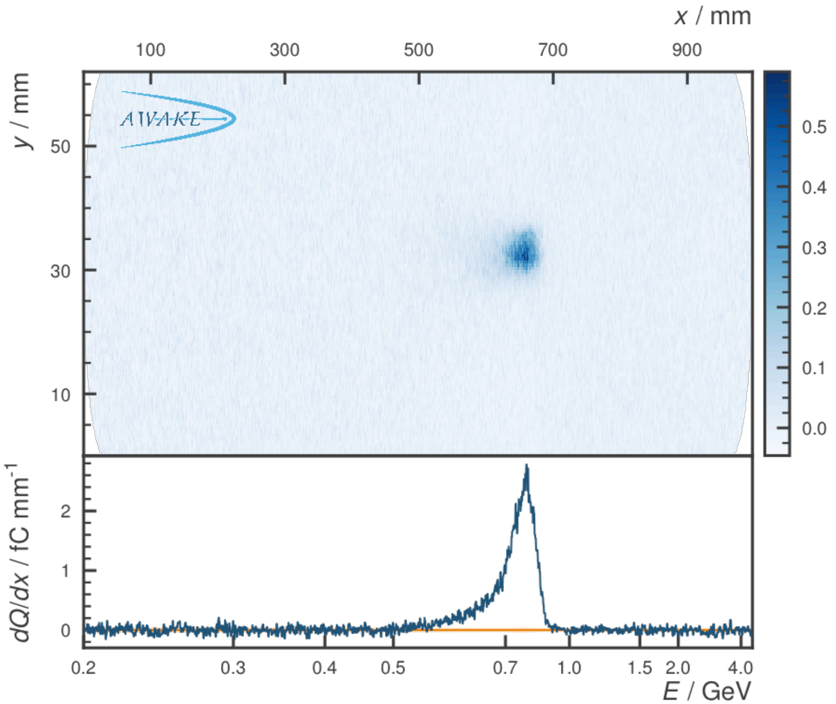
→ both OTR and CTR based measurements fit very well to predicted modulation frequency, for a range of plasma densities.

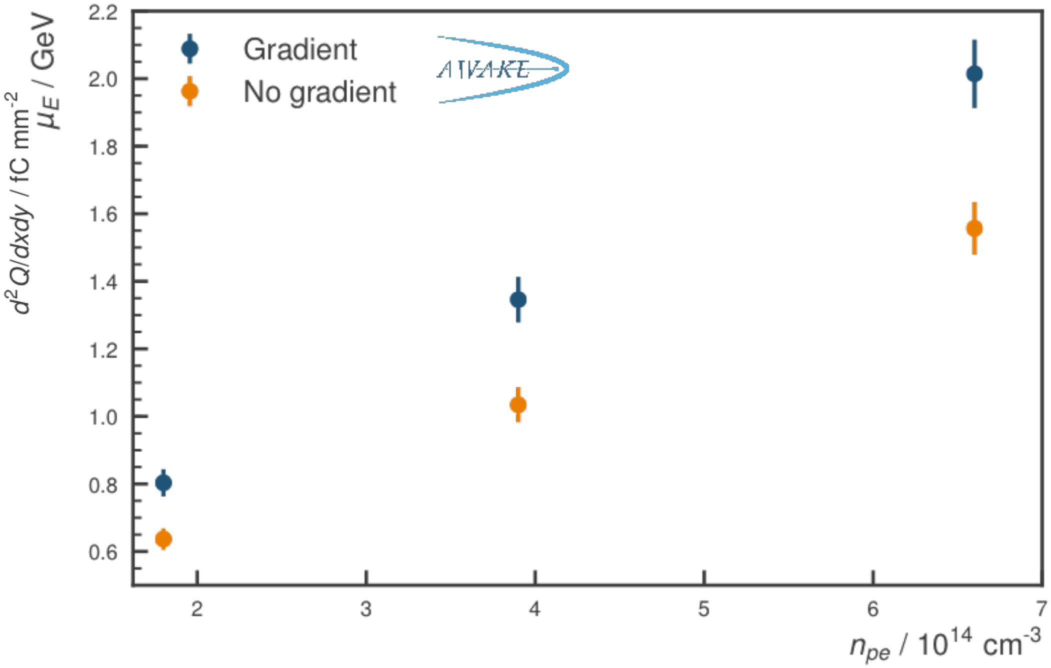
E. Adli et al.,(AWAKE Collaboration), PRL **122**, 054802 (2019)

AWAKE

Electron Acceleration Results

E. Adli et al., AWAKE Collaboration, Nature **561,** 363 (2018)





Note: we are accelerating 10 times more charge than previously thought (CLEAR calibration issue). Maximum accelerated charge ~100 pC (~20% of injected)

Electron acceleration in a proton-driven plasma wakefield works !

With todays existing proton bunches via seeded self-modulation!

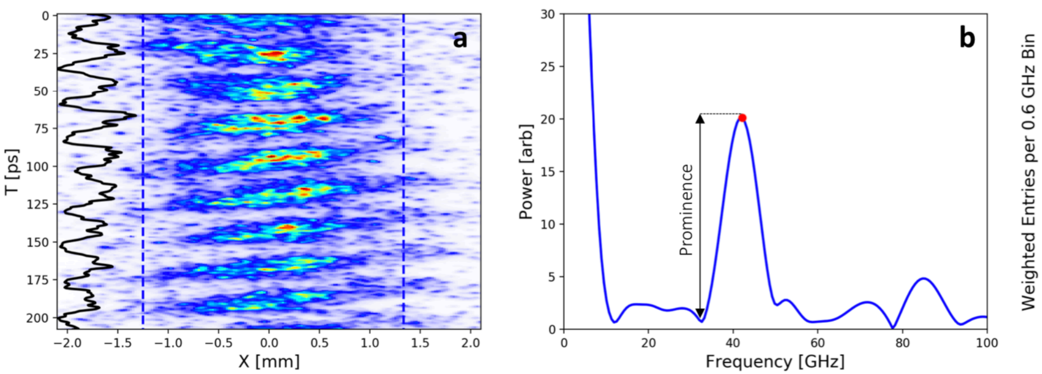
Ongoing Analyses of Run 1 Data

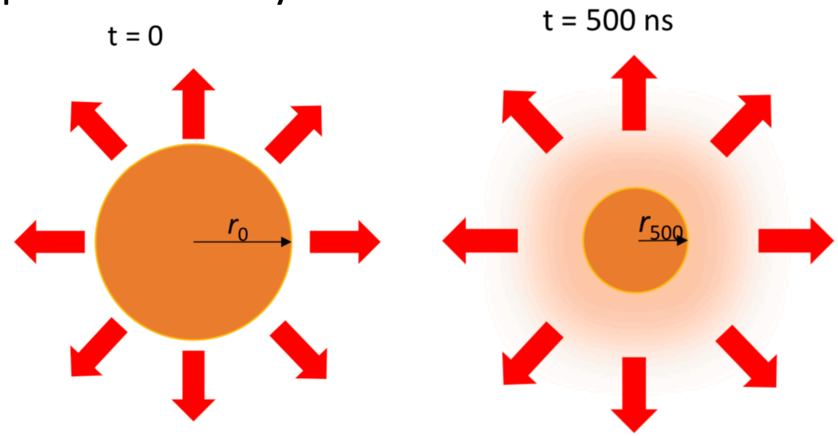
S. Gessner

(paper draft ready)

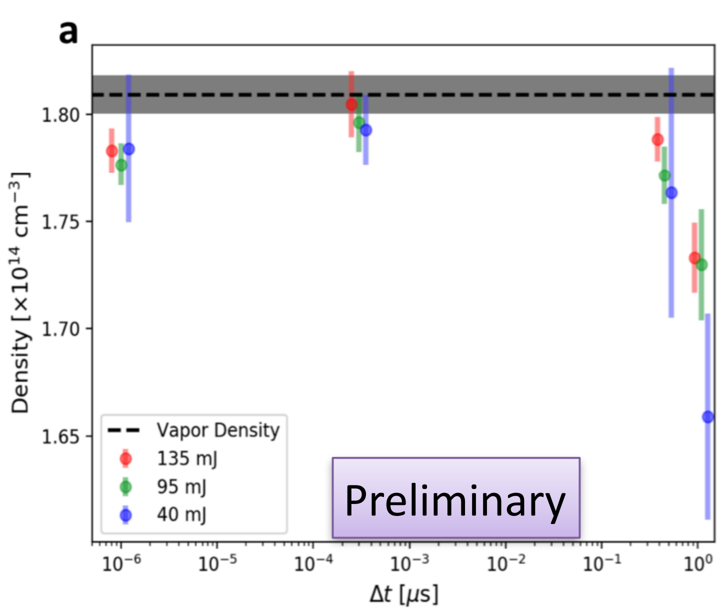
The plasma column is stable for significant time

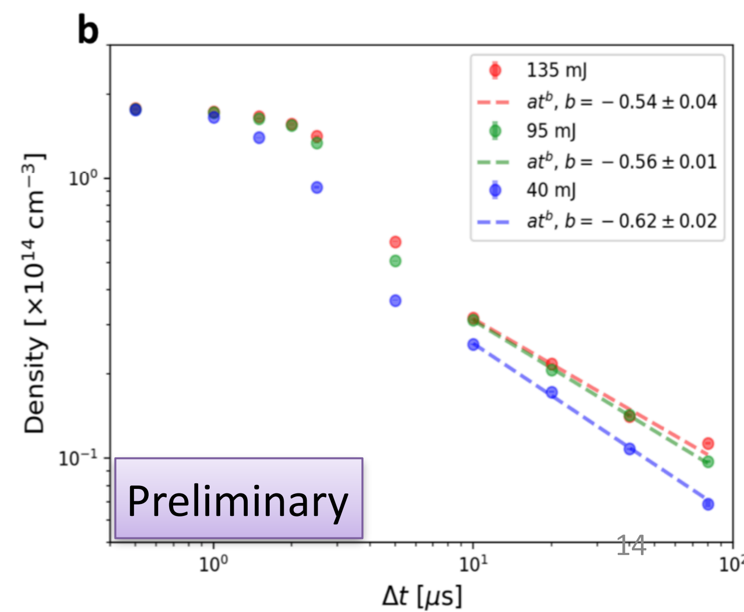
use proton bunch modulation frequency to determine plasma density





plasma density ~constant for several hundred ns. Important for Run 2 planning





Dr. Spencer Gessner

Simon van der Meer Early Career Award in Novel Accelerators

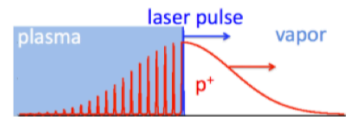
first recipient

Awarded at the EAAC19 workshop on Elba, 15-21 September 2019.

Ongoing Analyses of Run 1 Data

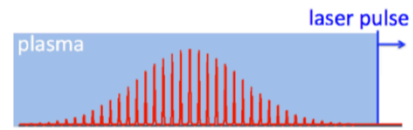
How far forward can we put the laser pulse to seed with ionization front?

"Seeding":



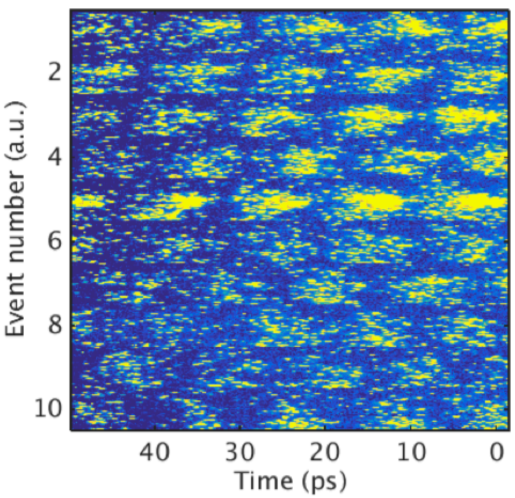
SSM

"No seeding":

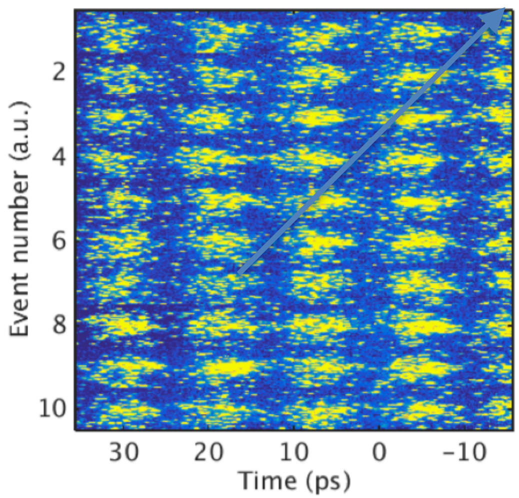


SMI

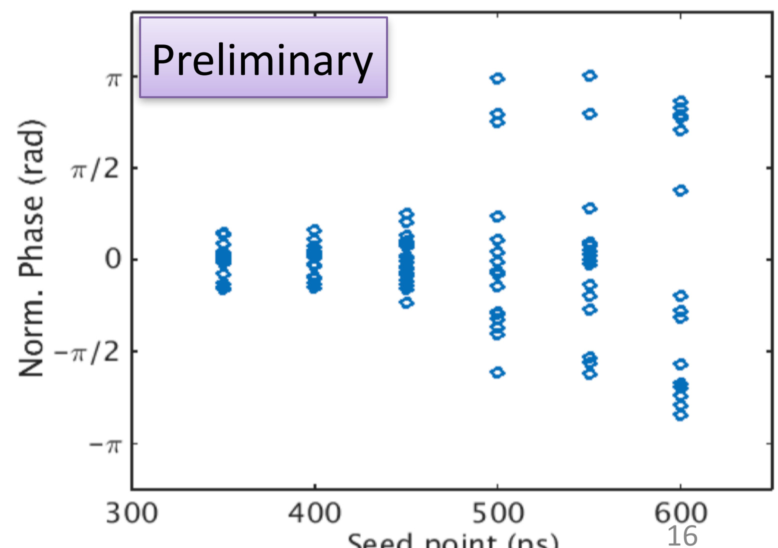
no seeding



with seeding



seeding ~stable up to 400ps=12cm forward of bunch center



F. Batsch, P. Muggli

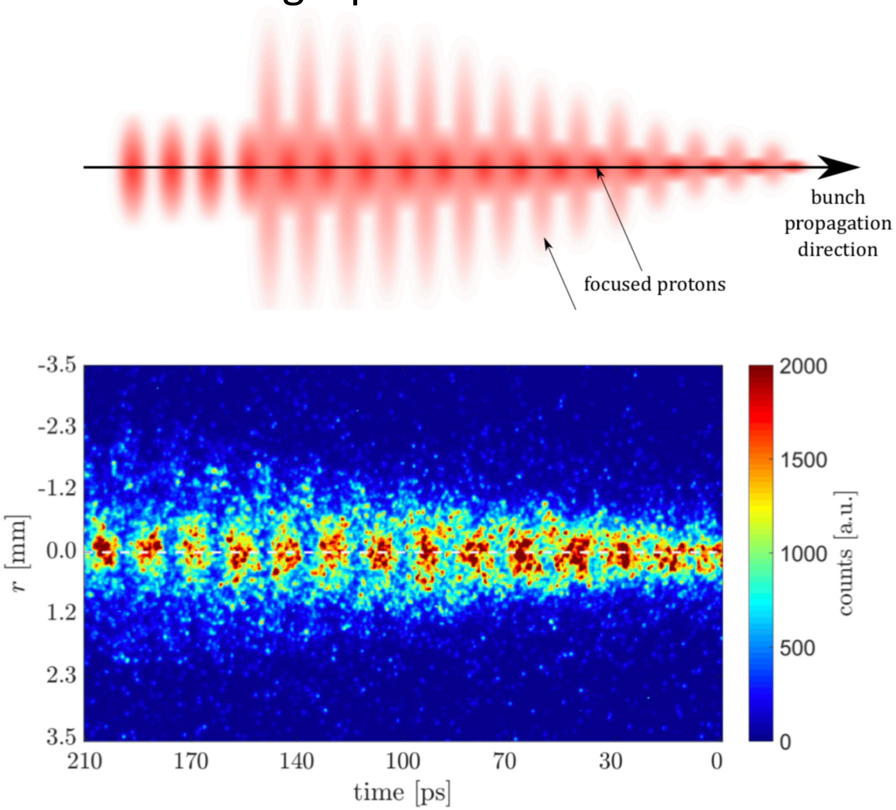
publication in preparation

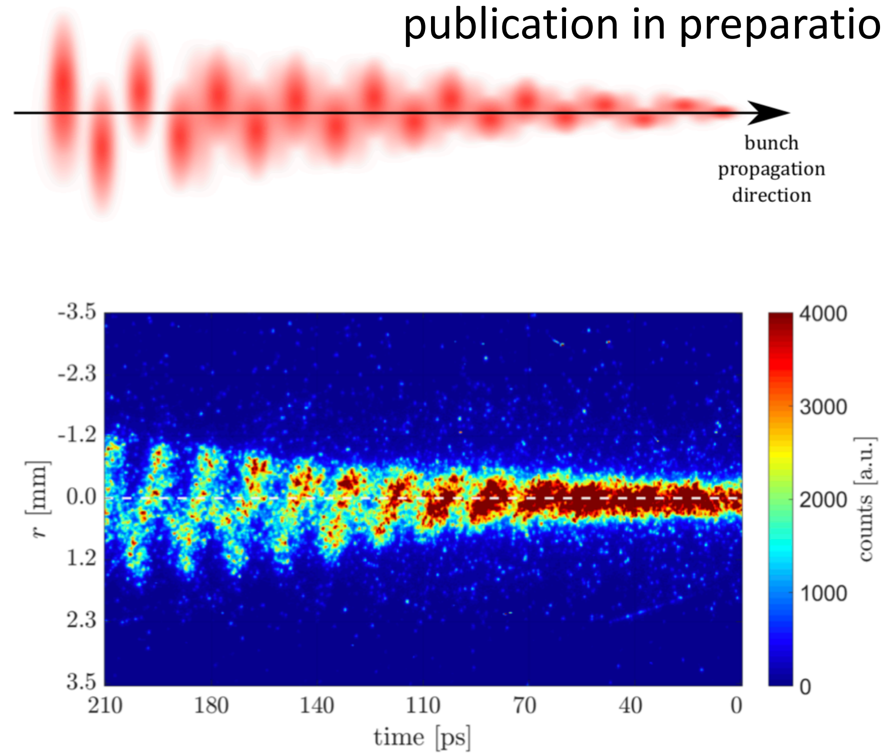
Ongoing Analyses of Run 1 Data

Is beam hosing a problem for AWAKE scheme?

M. Hüther, P. Muggli

publication in preparation





- Hosing is observed in AWAKE under particular experimental conditions ($n_{pe} \leq 0.7 \cdot 10^{14}\,\mathrm{cm}^{-3}$) different to the conditions used for electron acceleration experiments

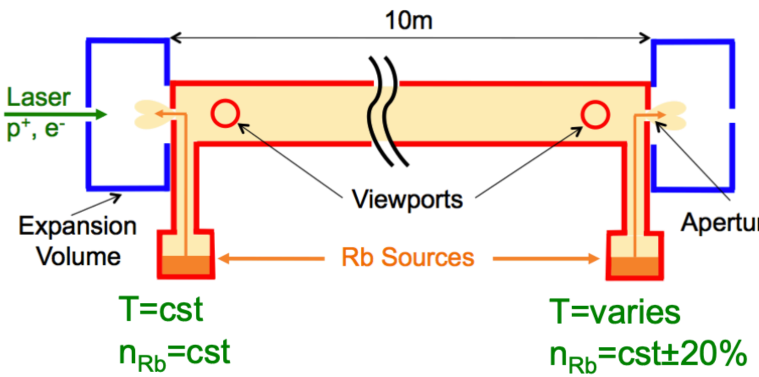
→ Hosing is not a limitation for AWAKE on a length of 10 m

Ongoing Analyses of Run 1 Data

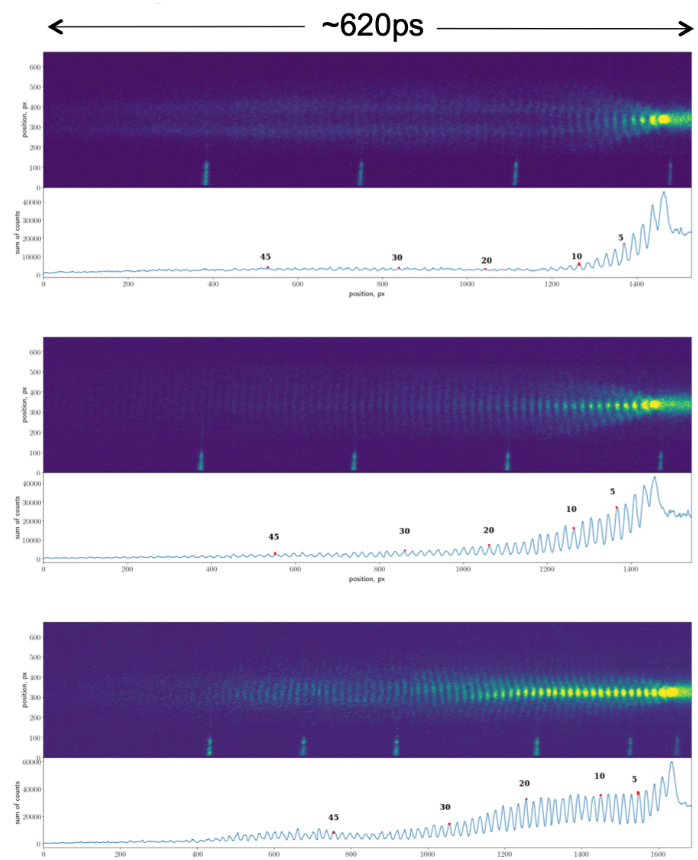
F. Braunmüller, T. Nechaeva et al

publication in preparation

How does the SSM depend on plasma density gradients?



Produce gradient by changing temperature of upstream Rb source



-20% grad

0% grad

+20% grad

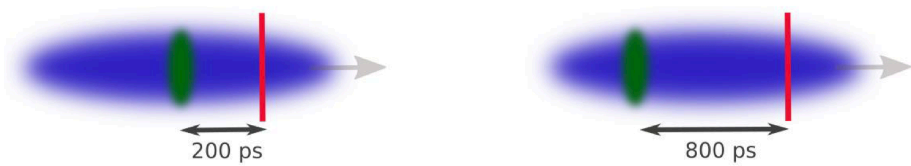
Analysis includes transverse development, CTR and streak camera data.

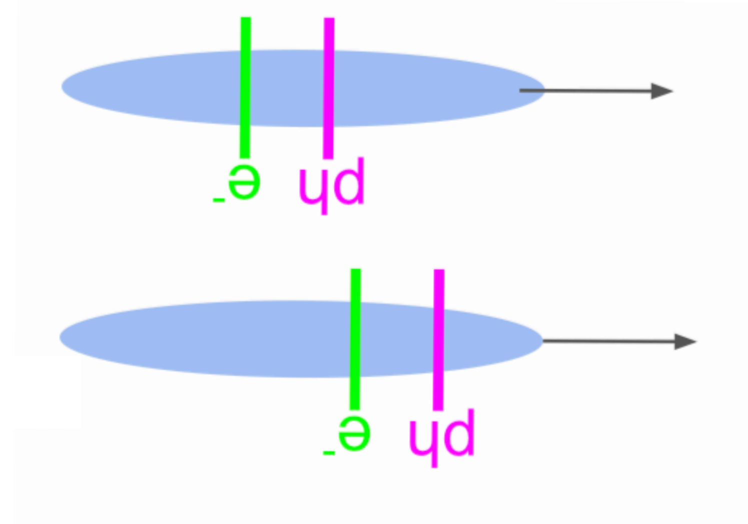
Clear differences in modulation pattern

Positive gradient gives improved results, as expected from simulation studies

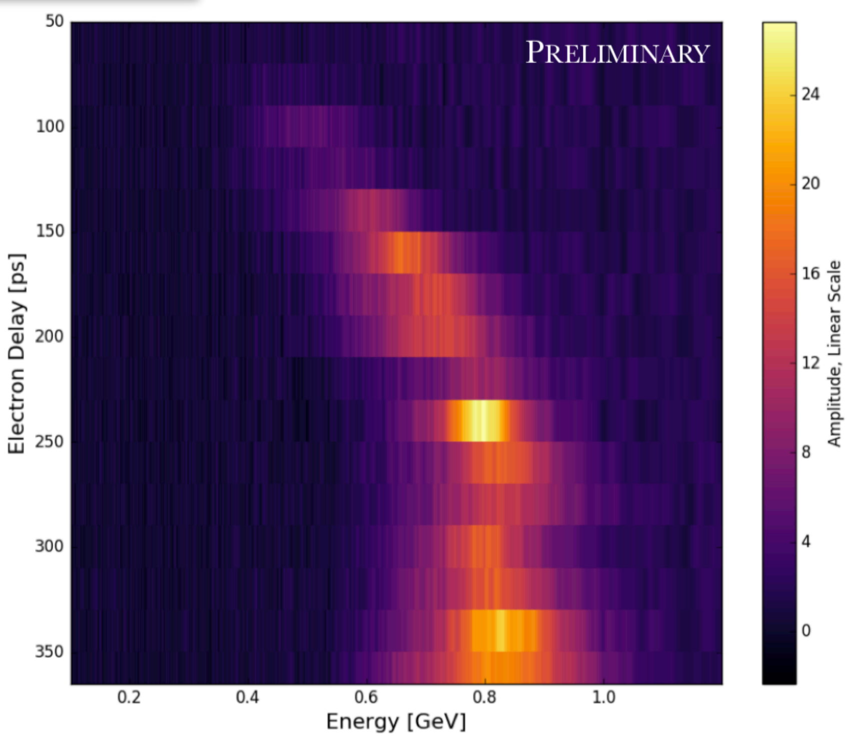
Ongoing Analyses of Run 1 Data

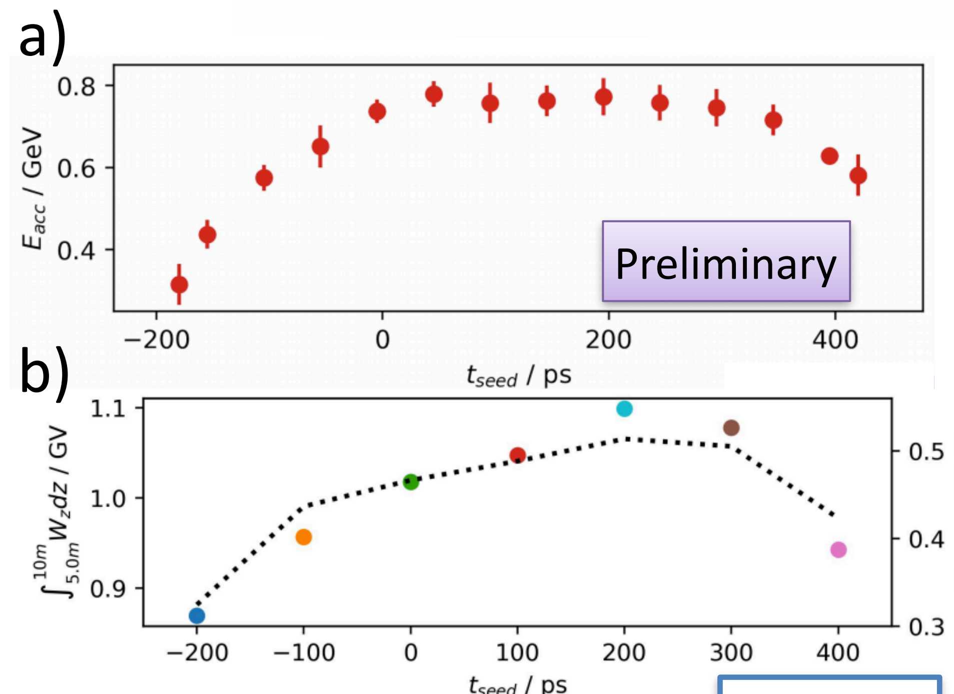
Dependence of electron acceleration on seeding location and electron injection delay





J. Chappell





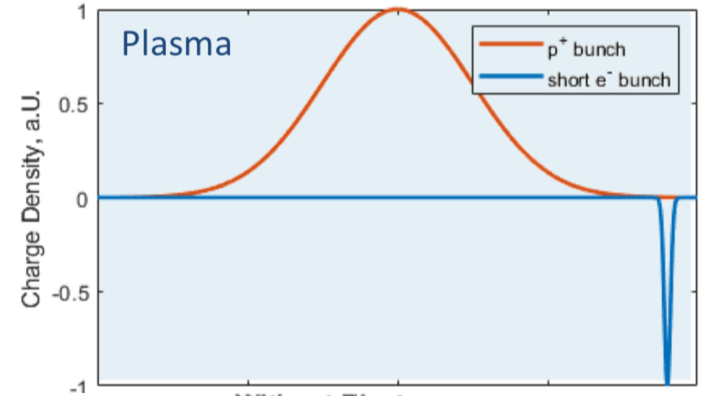
M. Turner

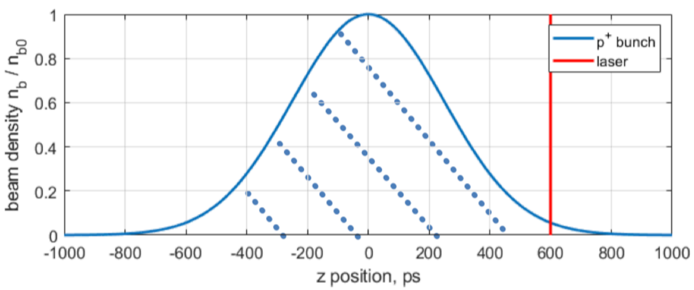
publication in preparation

Ongoing Analyses of Run 1 Data

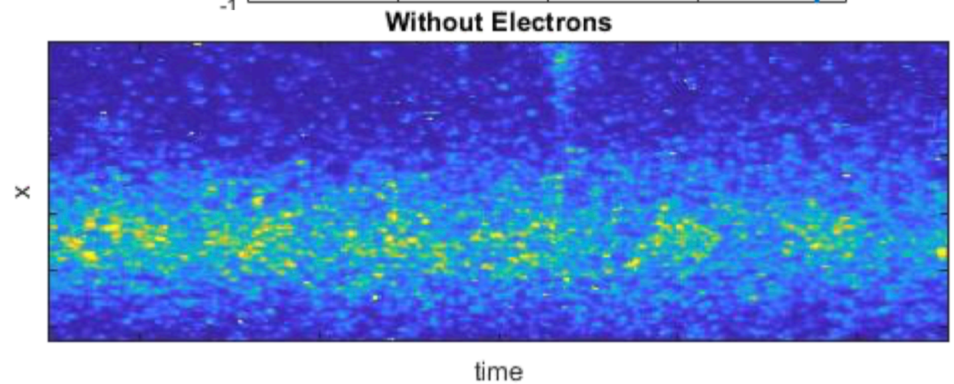
Can we replace laser seeding with electron seeding?

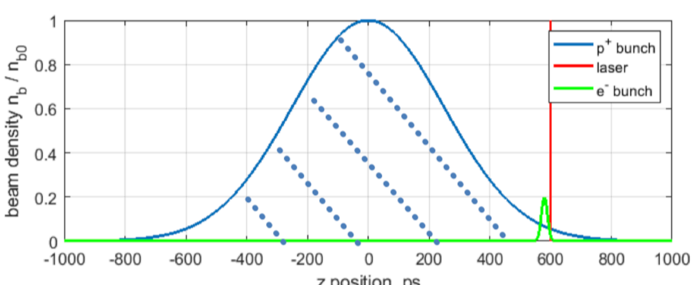
Important consequences for Run 2 planning



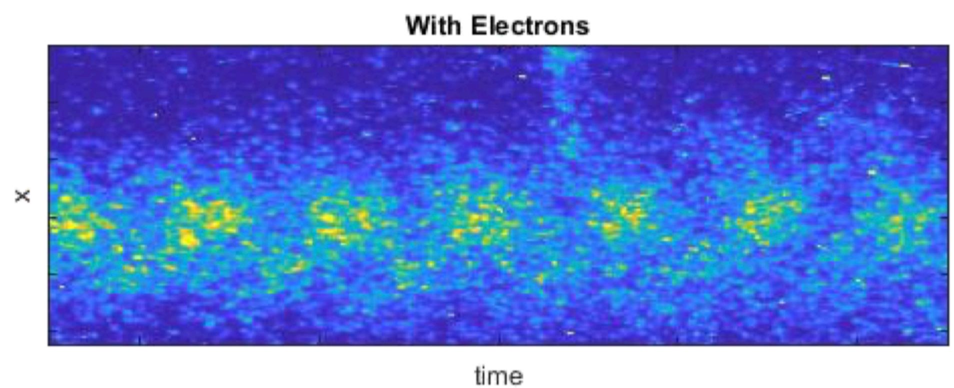


Without e^- bunch





With e^- bunch



A. Bachmann, P. Muggli

Indication: electron seeding works

Ongoing Analyses of Run 1 Data

There are a number of other investigations ongoing that I cannot report on due to lack of time:

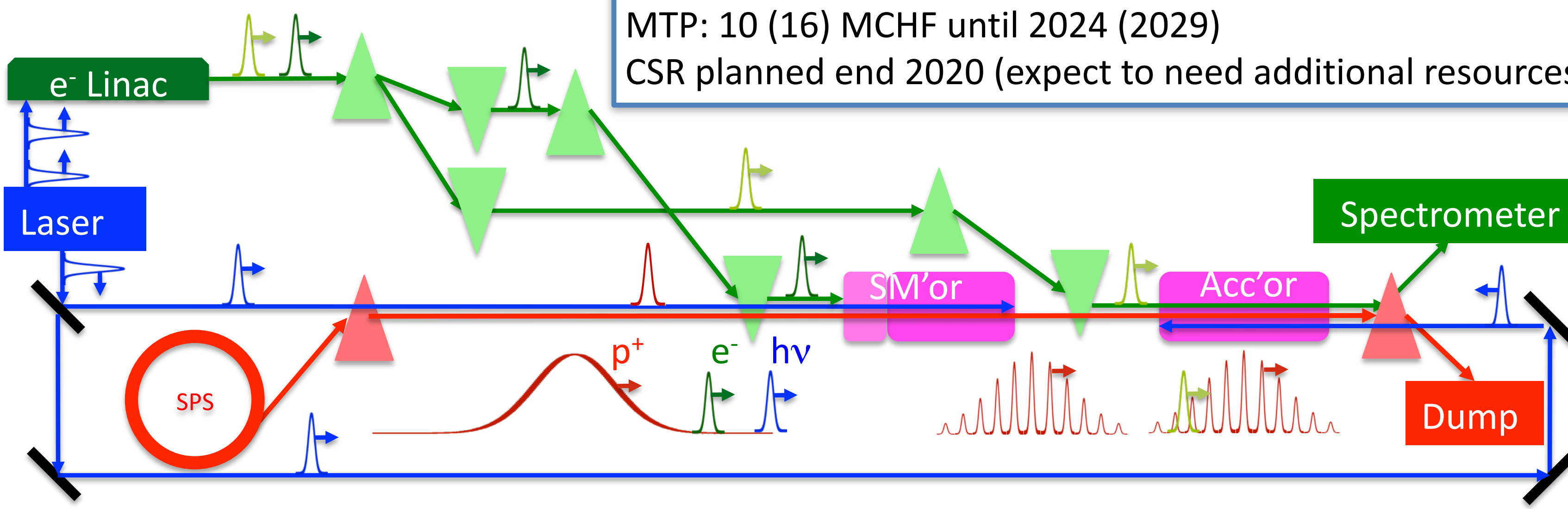
- detailed **comparison of simulations with data** (proton bunch defocusing as function of many quantities)
- detailed **study of proton bunch parameters** (important for simulations)
- detailed **study of electron beam line** and understanding of electron bunch parameters
- studies of the **propagation of the laser pulse in Rb** and the further measurements that have been performed in 2019
- **Partially stripped ion run** and its use as calibration check of the spectrometer system

Apologies to my AWAKE colleagues!

Run 2 (2021-2024)

Goals:
stable acceleration of bunch of electrons with high gradients over long distances
'good' electron bunch emittance at plasma exit
Be prepared to start particle physics experiment after Run 2

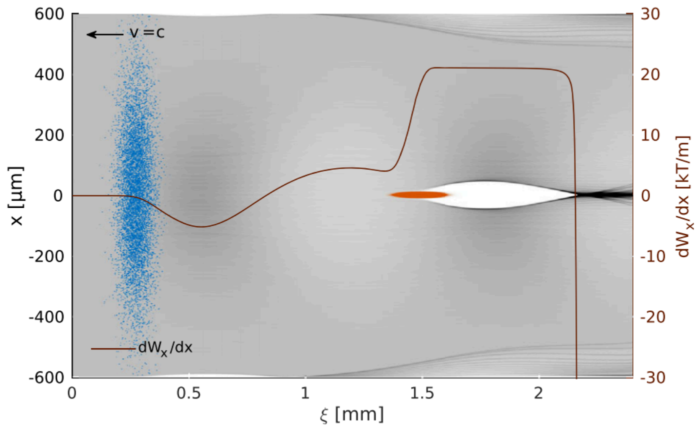
CERN funding for design study 3MCHF 2019-2021
MTP: 10 (16) MCHF until 2024 (2029)
CSR planned end 2020 (expect to need additional resources



Nominal design:
- electron bunch seeding
- x-band >150 MeV, 200 fs bunch for acceleration
- start with Rb plasma source technology
- Rb density step in SM cell
- Accelerator cell ionized from downstream end
- clear out CNGS target area to generate space, also for potential particle physics experiment

E. Gschwendtner, P. Muggli leading the studies

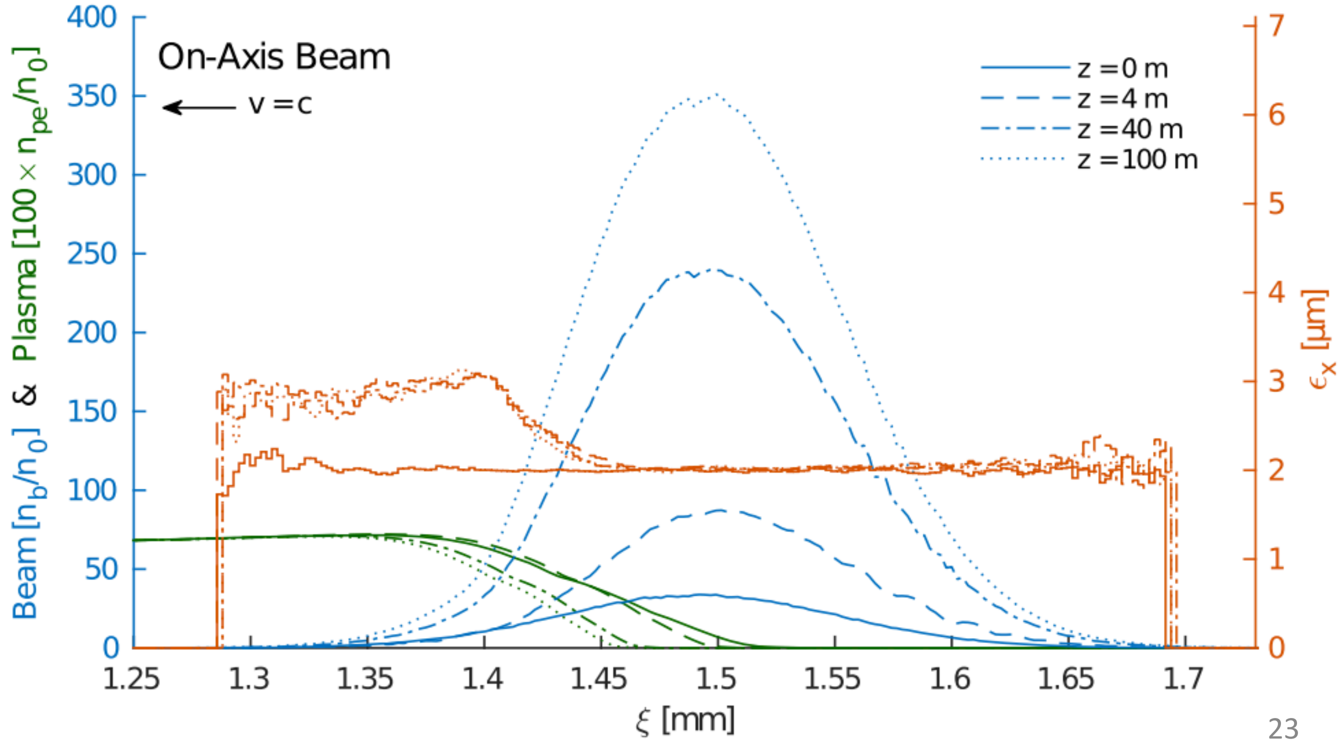
Run 2 study



Compact electron bunch can create its own 'bubble' emittance is preserved during acceleration

V.K. Berglyd Olsen, E. Adli and P. Muggli
Phys. Rev. Accel. Beams

The injection of a short electron bunch at the right phase allows propagation over long distances with no emittance growth (apart from the head of the bunch)



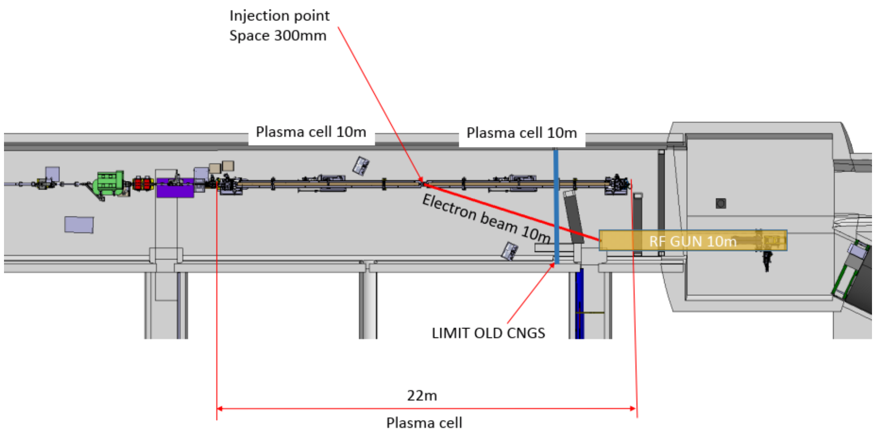
Run 2 study

electron source and beam line studies

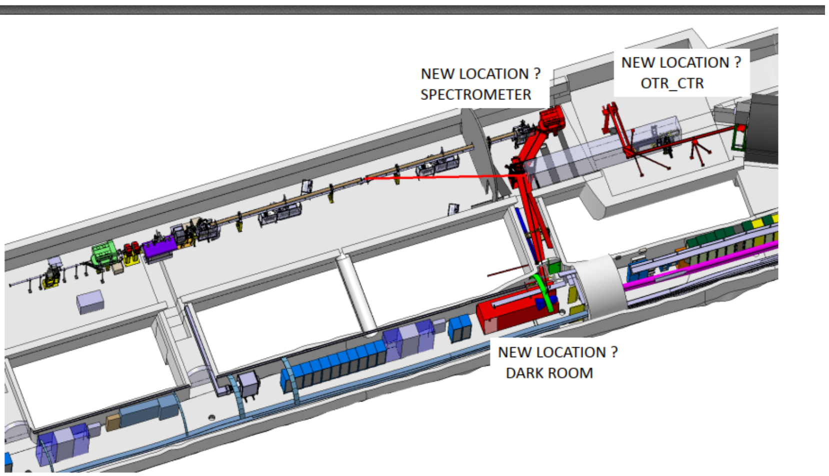
R. Ramjiawan and F. Velotti

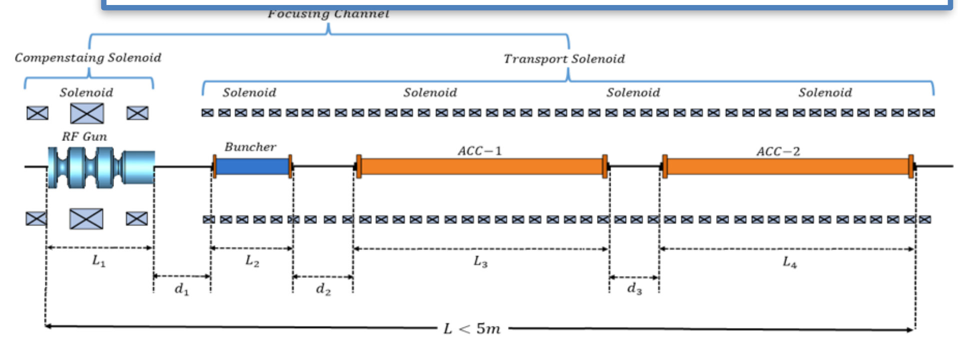
S.-Y. Kim, M. Kelisani, S. Doebert, L. Garolfi

Footprint investigation



HYPOTHESIS B

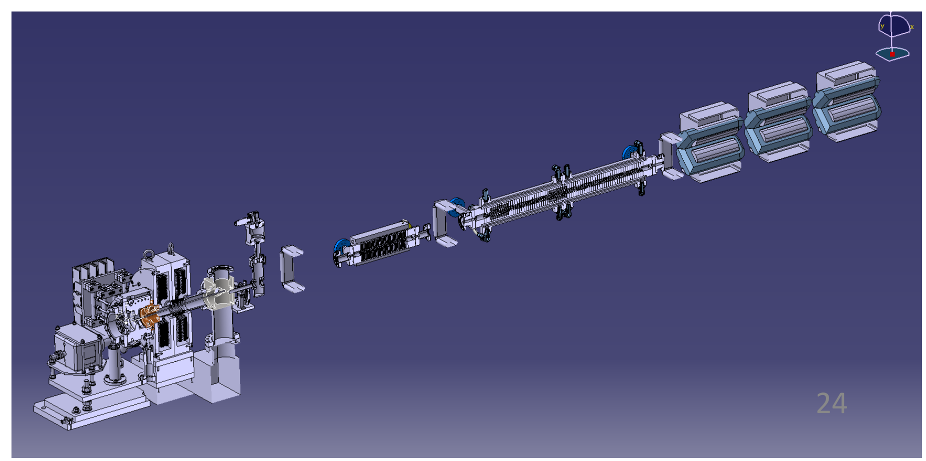




X-band accelerator structure

Simulation studies show that we can achieve our desired parameters with this scheme!

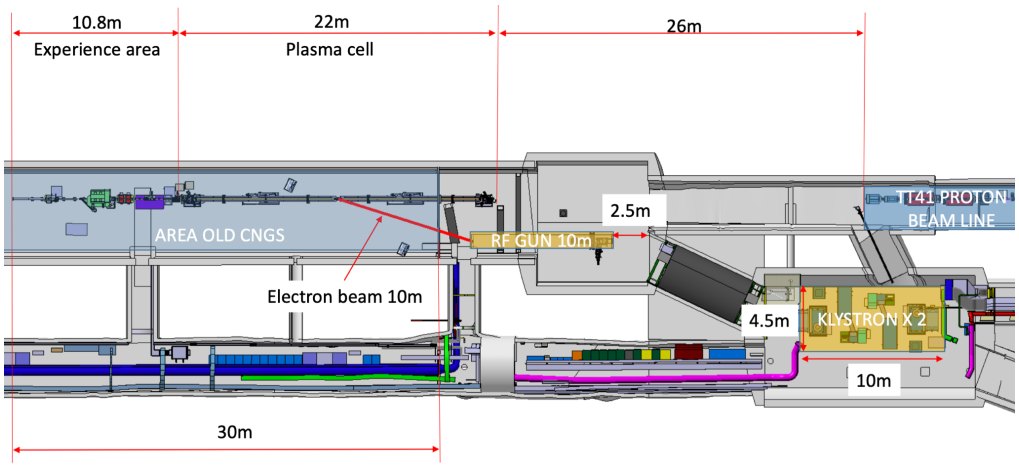
CLEAR as first test realization

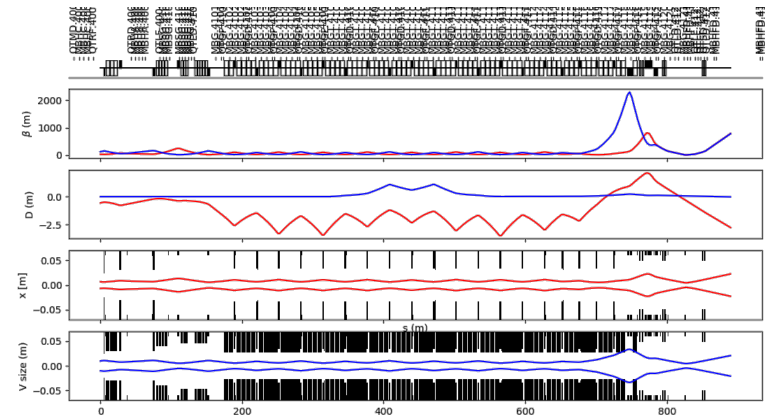


Run 2 study

Proton beam line study:

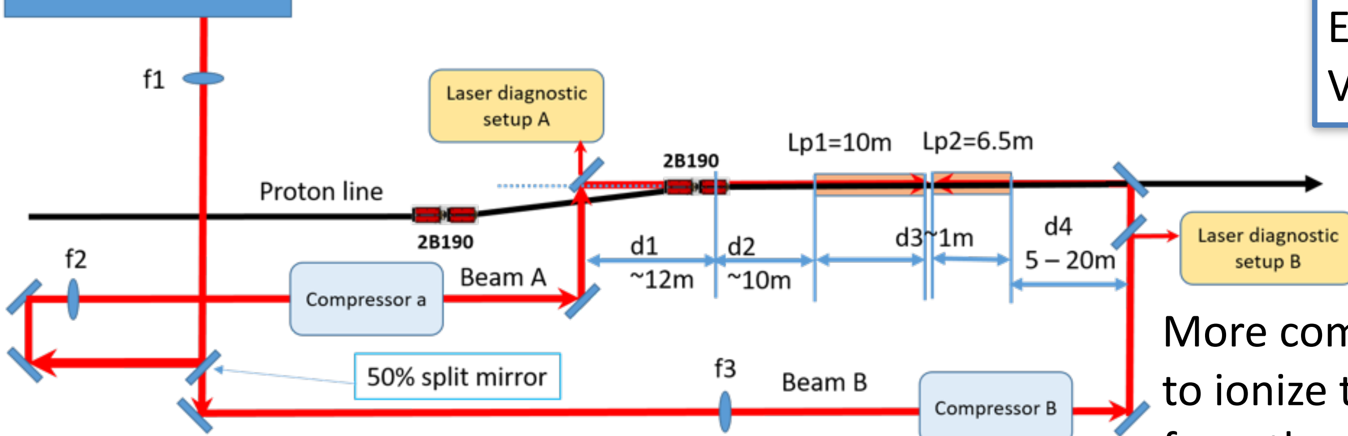
R. Ramjiawan, F. Velotti





The same proton bunch parameters as available for Run 1 will be available.

Laser beam lines



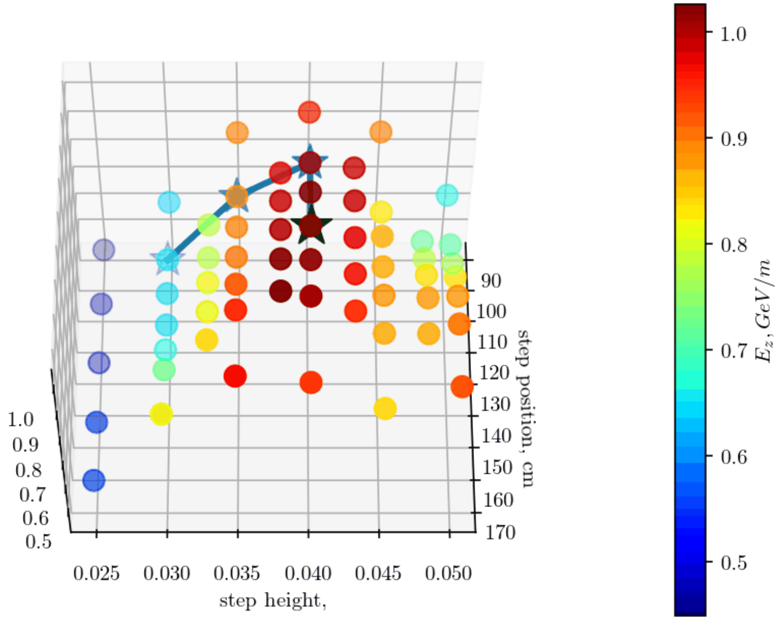
E. Granados, J. Moddy, V. Fedosseev, H. Panuganti

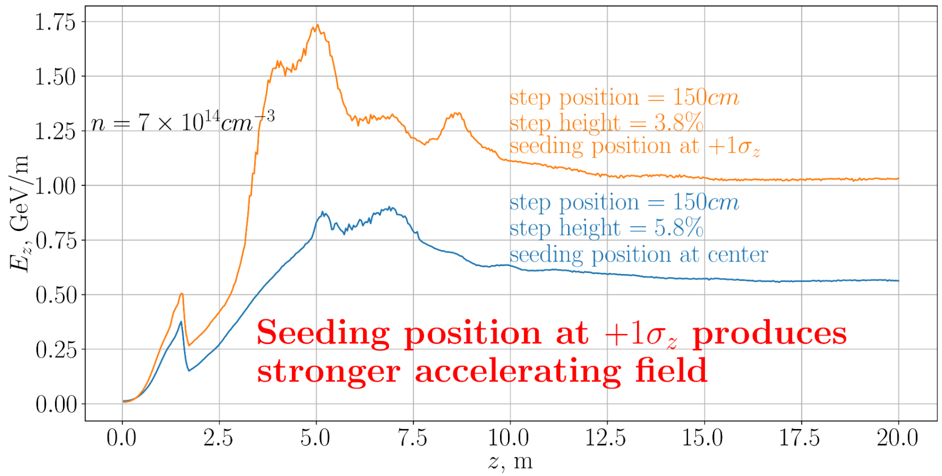
More complicated due to the need to ionize the second Rb source from the rear.

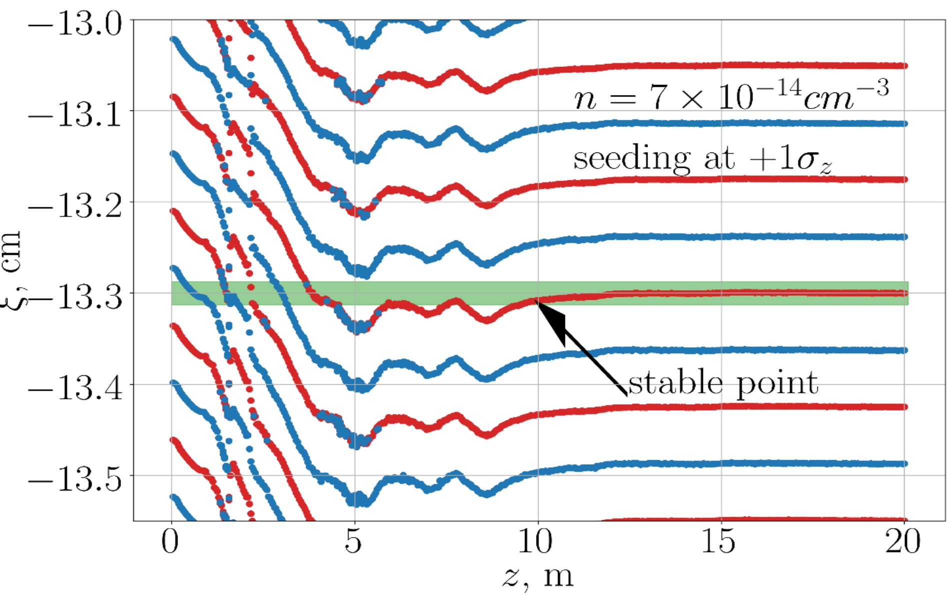
Run 2 study

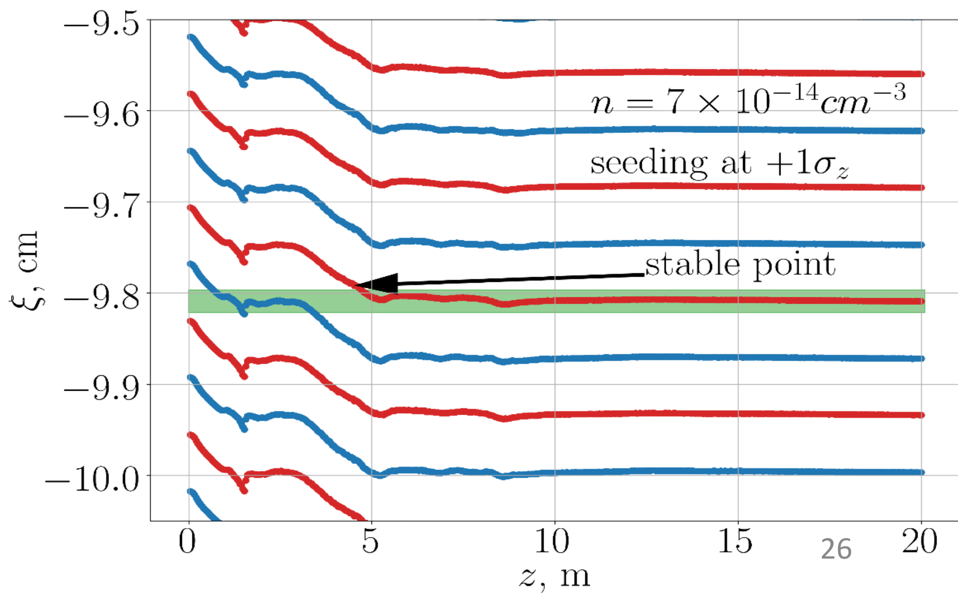
Simulation: expectations from density step in SSM cell - systematic investigation

K. Lotov et al.







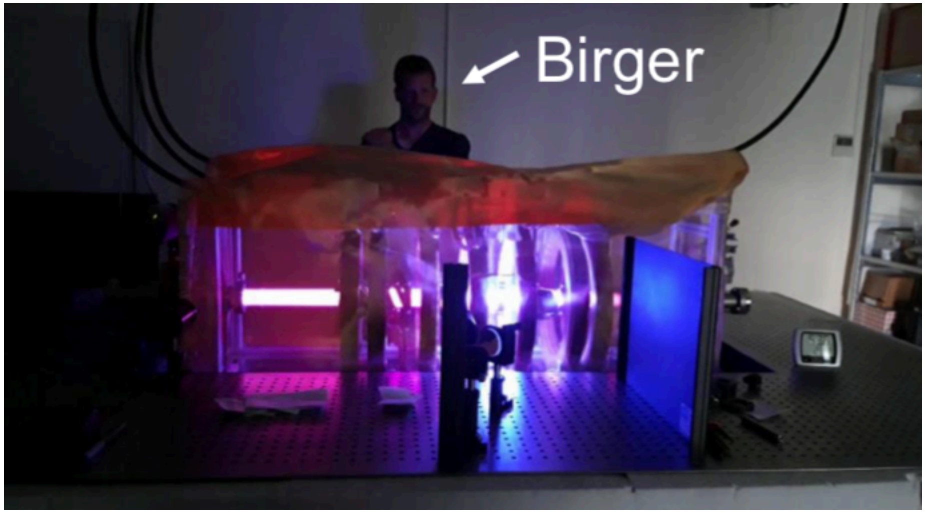


Run 2 study

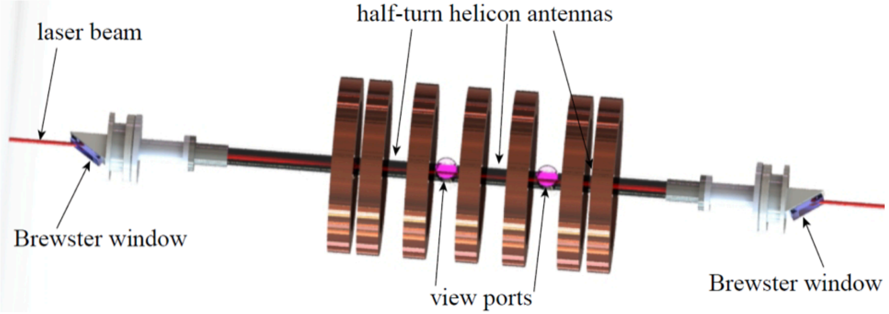
Helicon Cell development @ CERN

A. Sublet, B. Buttenschön, O. Grulke, et al.

Density needed for AWAKE achieved at the IPP in Greifswald. Study uniformity, scalability at CERN. New laboratory.



Successful commissioning of helicon plasma source @ CERN



Schematic of a TS diagnostics in AWAKE

R Agnello, I. Furno

A suite of new diagnostics will be used to understand the features of the plasma.

Here: Thomson Scattering concept (SPC)

We also plan to install and test discharge plasma sources in the new laboratory (N. Lopes)

Particle Physics Applications

We have actively participated in the EPPSU exercise - several documents submitted

- **Physics with a high energy electron beam**
  - search for dark photons in beam dump experiments
  - Fixed target experiments in new energy regime

Energy & Flux important - luminosity determined by target properties. Much more relaxed parameters for plasma accelerator

- **Physics with an electron-proton or electron-ion collider**
  - Low luminosity version of LHeC
  - Very high energy electron-proton, electron-ion collider

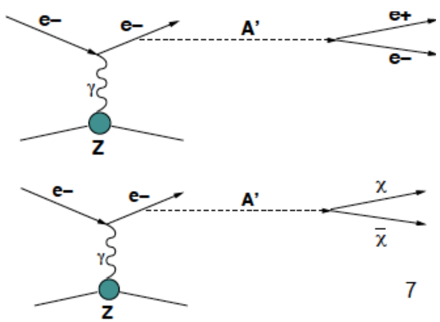
New energy regime means new physics sensitivity even at low luminosities !

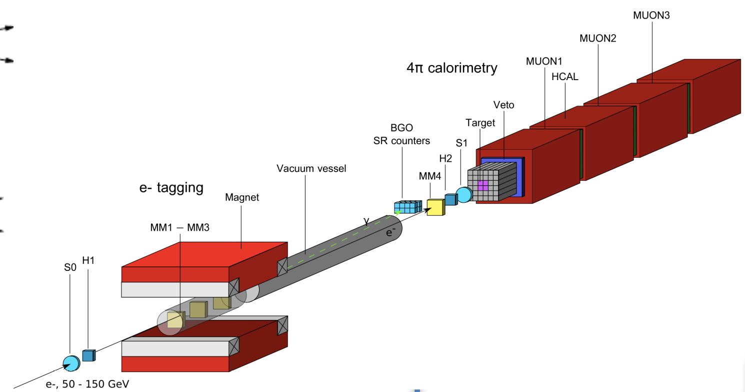
- **To be evaluated:**
  - AWAKE-like scheme with ions
  - acceleration of muons in LEMMA scheme
  - AWAKE-like scheme with FCC

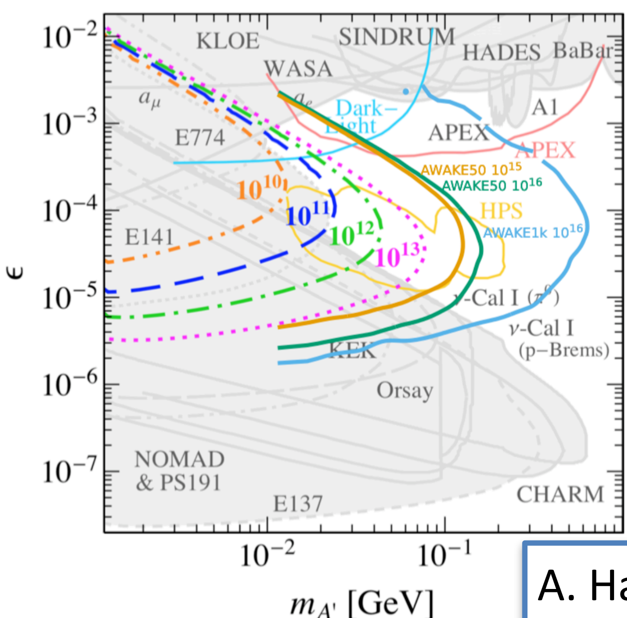
We have just started to evaluate the particle physics potential of plasma acceleration. Need creative thinking !

Dark Photon Search

NA64-like experiment with parameters that could become available with AWAKE-like acceleration of electrons using the SPS proton bunches



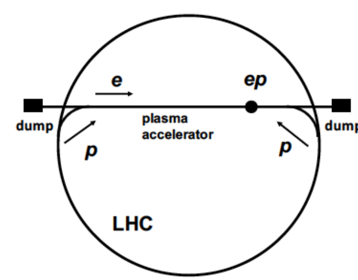


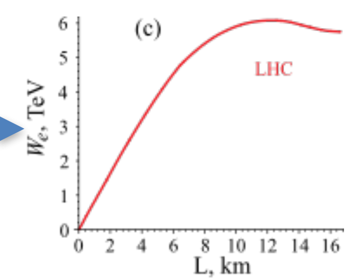


A. Hartin, M. Wing

Fixed Target

LHC Driver





$$E_{\rm CM} = \sqrt{2 M_P E_e} = 75 \text{ GeV}$$

Compass: ~20 GeV

EIC: 15-140 GeV

A. Caldwell, K. Lotov, M. Wing

Summary

Goal for AWAKE run 1: demonstrate modulation process (done) and proton-driven acceleration of electrons before LS2 of the LHC (done).

Acquired data under further analysis - several papers approaching submission

Run 2 proposal developing: goals are demonstration of stable acceleration and good electron bunch properties. We want to demonstrate possibility to use AWAKE scheme for particle physics applications by LS3

Long term prospects for proton-driven PWA exciting ! Starting to develop particle physics program that could be pursued with an AWAKE-like beam.